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OPERATIONS WITH THE SPECIAL PURPOSE DEXTROUS MANIPULATOR ON SPACE STATION FREEDOM

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ABSTRACT

SPAR Canada is actively participating in the Space Station Freedom Program by contributing the Mobile Servicing System (MSS) which will be involved in assembly, maintenance and servicing of both the Space Station and the MSS itself. Part of the MSS is the Special Purpose Dextrous Manipulator (SPDM), a two armed dextrous robot with advanced vision and manipulative capabilities. In addition to Space Station and payload servicing activities the SPDM will be designed to perform self maintenance on the MSS itself. The majority of Space Station equipment will be on orbit for the anticipated 30 year lifespan and the maintenance philosophy will be to repair by the exchange of Orbit Replacement Units or ORU's.

This paper describes the present concept, configuration and operation of the SPDM and the detailed simulations associated with the maintenance of part of the MSS. The Design Reference Mission presented in this paper is the replacement of a Joint Drive Module on the Canadian large payload manipulator, the Space Station Remote Manipulator System.

Other Design Reference Missions that have been investigated are briefly described, and future operations activity to support the definition of SPDM requirements are discussed.

ACRONYMS AND MNEMONICS

DRM	*Design Reference Mission*
EVA	*Extra Vehicular Activity*
EVR	*Extra Vehicular Robotics*
FSE	*Flight Support Equipment*
JDM	*Joint Drive Module*
LEE	*Latching End Effector*
MBS	*MSS Base System*
MSS	*Mobile Servicing System*
MMD	*MSS Maintenance Depot*
MT	*Mobile Transporter*
ORU	*Orbit Replaceable Units*
SSF	*Space Station Freedom*
SPDM	*Special Purpose Dextrous Manipulator*
SSRMS	*Space Station Remote Manipulator System*
TCM	*Tool Changeout Mechanism*

INTRODUCTION

The Special Purpose Dextrous Manipulator (SPDM) is an element of the Mobile Servicing System (MSS) which is the Canadian contribution to the International Space Station Freedom Program as defined in the Memorandum of Understanding between Canada and the USA. The MSS provides hardware for: the assembly and external maintenance of the Space Station: the servicing of attached payloads; the transport of payloads and hardware about the Station; the deployment and retrieval of free flyers; the berthing of vehicles such as the Space Shuttle; the support of Extravehicular Activity (EVA) and support of Space Station Operations including safe haven requirements. The MSS is being designed to be self maintainable, a unique and novel feature on the Space Station. The SPDM will provide the dextrous robotic capability to maintain the MSS and thus reduce use of EVA which is both hazardous and expensive.

CONCEPT

Extra Vehicular Activity (EVA) is a time consuming, expensive and potentially dangerous operation. Any viable method to reduce EVA must be given serious consideration. As evidenced by recent NASA studies (Fisher-Price, External maintenance Task Team), considerable thought is being given to the use of robotics for routine maintenance tasks on the Space Station. Repair from failure conditions and routine maintenance is performed by the changeout of Orbit Replaceable Units or ORU's. Ultimately all activities have to be achievable by EVA to cover the case of robot failure or Station resource failure (Loss of Power, Data,Video,communications). Logically, therefore, it follows that a dextrous robot should have the ability to perform tasks in confined environments where access has been determined by a suited astronaut. The SPDM must be capable of performing the following tasks, with appropriate tools: - Exchange ORU's of up to 600 Kg mass - connect/diconnect utilities - Mate/demate connectors in single or staggered rows, as little as 4cm apart in single rows - Attach/Detach interfaces - Provide lighting to the work area or EVA crew - Monitor the work area or the EVA crew by closed circuit TV - Clean surfaces - Remove/install thermal covers and blankets - Perform various inspections

The minimum and maximum reach envelopes, access restrictions and tip torques were originaly specified for the SPDM based on EVA capabilities. Robots that have to perform human-like tasks do not, however, have to have the same anthropomorphic design. For example the SPDM body can fold/unfold allowing access to difficult work volumes; an EVA astronaut could acomplish the access problem by relocating to a different foot restraint location. The DRM that follows is the present driver for the overall reach requirement of the SPDM, one of the many derived requirements that will ultimately be investigated and verified by DRM's.

CONFIGURATION *(Figure 1)*

The SPDM consists of a base section, an articulated body, two seven degree of freedom arms and a head with vision and lighting sytems.

The Base section has a length of around 1.8 metres and has one roll joint.The base supports the articulated sections of the manipulator and consists of a latching End Effector so that the SPDM can grapple and operate from a Power Data Grapple Fixture (PDGF); power, data and video resources pass across

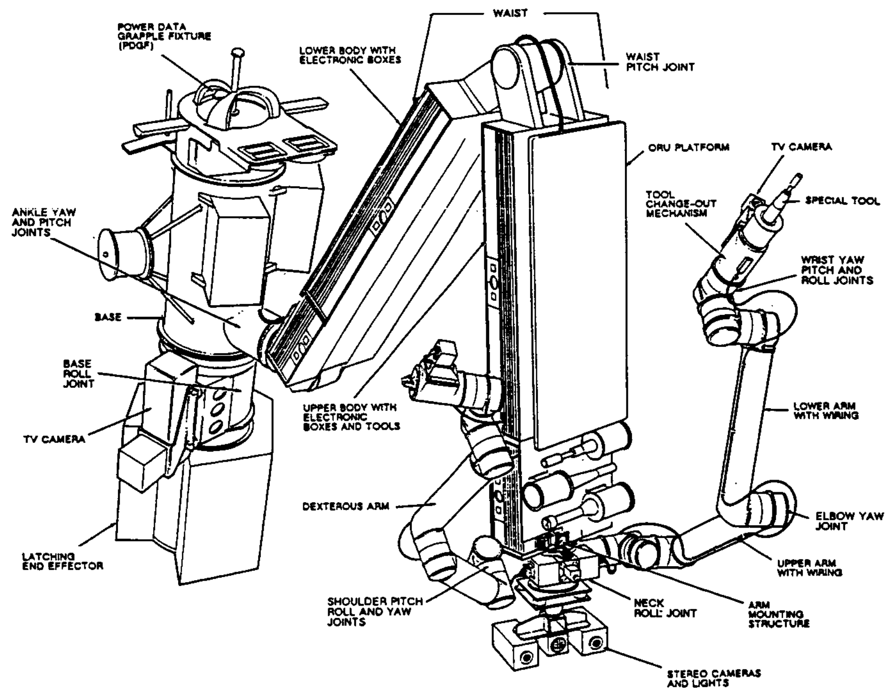


FIGURE 1 SPDM CONFIGURATION

the PDGF interface. A video camera provides visual information for berthing the End Effector. PDGFs can be located at strategic worksites on the Space Station Truss, modules and on the various elements of the MSS itself. At the other end of the base is a PDGF which can be grappled by the Space Station Remote Manipulator System (SSRMS). The SPDM can therefore be carried and operated from the end of the SSRMS. Accessibility is therefore greatly enhanced as the SSRMS and its Mobile Remote Servicer system and Mobile Transporter can reach most areas on the Space Station requiring servicing activities.

The Body sections provide temporary storage for Orbit Replaceable Units (ORU's) and accommodation for the SPDM electronic processors. Tools will also be stored on the body. The body is attached to the base by a pitch and yaw joint and the central articulation is a pitch joint.

Each of the two arms are presently configured with seven degrees of freedom, each carries a Tool Changeout Mechanism (TCM) which provides interfaces between the arm itself and the servicing tools. Tools can be changed as required during operations, a video camera could also be carried as part of the TCM. Force moment sensing is to be included in the arms. Joint electronics and integrated thermal protection are also incorporated in the arms themselves.

The neck and head system allow for growth to stereo vision and it is intended to include an artificial vision function which will allow automatic tracking and grappling of ORU's, tool alignment and ORU identification. The head and neck includes both pan and tilt units and artificial lighting.

When completely folded for storage and launch the SPDM occupies a volume with dimensions of approximately 2500x876x1435 mm. The SPDM in its stowed configuration requires minimal Flight Support Equipment and is presently manifested to fly with the MSS Maintenance Depot (MMD) on flight 8 (OF-1). A current concept for SPDM launch packaging is to utilize the MMD itself or the unpressurized Logistics Sub-Carrier.

OPERATION

The SPDM is capable of operating from the end of the SSRMS, from operating locations on the MSC, MMD and from PDGF's positioned on the Space Station structure. *(Figure 2)*

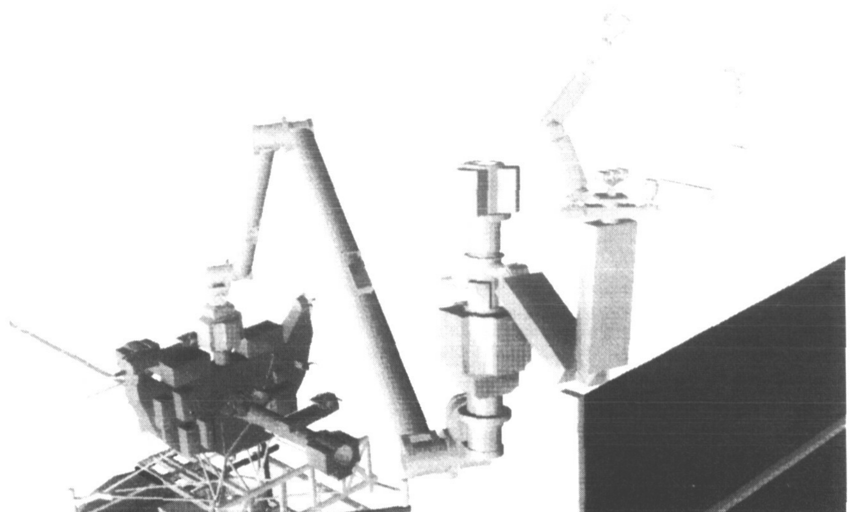


FIGURE 2 MSC WITH SPDM ON THE SSRMS

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

When operating from the end of the SSRMS, the SPDM PDGF on the base is grappled by the large arm and then positioned close to the area of operations. Due to the flexibility of the SSRMS, one of the SPDM arms would be used to grasp a stable piece of structure while the other arm would perform the dextrous task. An effective load path and sufficient stiffness would thus be achieved by using one arm as a stabilizer.

The MSS is designed to have several PDGF's to serve as operating locations for the SPDM. On the Mobile Remote Servicer Base System (MBS) there are two PDGF's capable of supporting SPDM operations. From these positions on opposite sides of the base the SPDM can access all the ORU's associated with the MBS and the SSRMS. The SPDM can therefore provide the robotic capability to maintain its parent system. The changeout of an SSRMS Joint Drive Module is examined as a Design Reference mission later in this paper.

PDGF's at strategic locations on the Space Station can also support SPDM operations. Present PDGF locations on the Space Station are on one of the forward nodes, the U.S. Laboratory Module and the Japanese Module.

The MSS Maintenace Depot (MMD) is at a fixed location on the truss where MSS specific spares and tools are stored and can be accessed for MSC maintenance. The Mobile Transporter can position the MSC on an adjacent truss bay to the MMD and allow the SPDM to collect tools and spares and also operate from the MMD.

One of the most versatile features of the SPDM is its ability to be carried by the SSRMS and in turn to carry a payload and also perform dextrous tasks on that payload. Such a unique capability is particularly useful during assembly operations that require positioning of payloads prior to attachment to Space Station structure or truss, the final interface manipulations being performed by the SPDM. EVA is thus reduced during the critical periods of Space Station construction. *(Figure 3)*

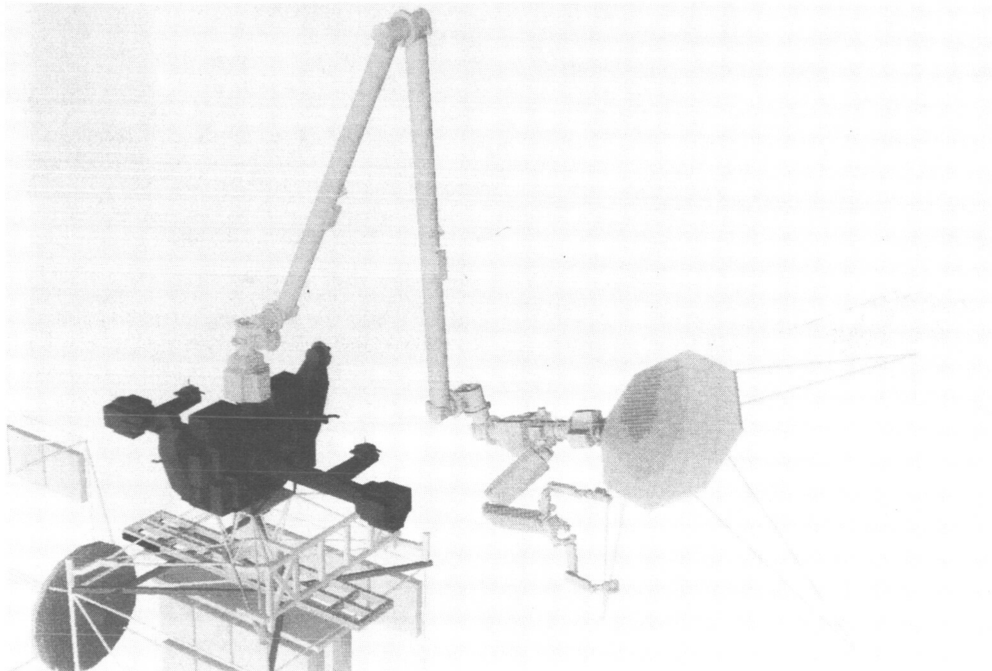


FIGURE 3 SSRMS/SPDM OPERATING ON PAYLOAD

CONTROL STRATEGY

The SPDM will be controlled teleroboticaly from a workstation inside the IVA environment. Force moment sensing and accommodation will be implemented from the start. As experience grows a number of more advanced features will be incorporated including an advanced vision system capable of direct ORU identification, auto tracking and capture and automated replacement.

There will be three modes of operation:

a) Manual Augmented mode

The human operator would input commands which would cause the motion of the arms to a particular Point Of Resolution in the task space.

b) Single Joint Mode

Individual joints of the SPDM manipulator could be commanded in rate or position mode.

c) Automatic Trajectory Mode

The control capabilities provide signals to command the manipulator along prescribed trajectories, the trajectories may be generated from stored information, POR target point coordinates or by vision system tracking signals.

DESIGN REFERENCE MISSIONS - PHILOSOPHY

The Space Operations group at Spar, in conjunction with NASA, have developed a series of Design Reference Missions which are realistic assembly and maintenance scenarios on both the Space Station and the MSS itself. One of the present principal design drivers for SPDM configuration and capabilities is the ability of the MSS to service itself. The MSS is a unique system on the Space Station, a robotic system that is largely autonomous and also capable of self maintenance. The MSS is one of the most complex systems on the Space Station and if the SPDM can maintain the MSS it will likely be able to maintain other SS equipment. Operations are therefore in a unique position to influence the requirements for the SPDM from an end user standpoint. The DRM's influence such factors as physical dimensions, joint angles and rates, working envelopes and fault tolerance architecture. As part of the studies, viewing analysis are underway to show the obstructions and lighting difficulties. Tools and ORU interfaces are also being studied.

MAINTENANCE CONCEPT

All systems on the Space Station are design to have an operational life of at least 30 years. Maintenance on orbit is achieved in the unpressurized environment by the exchange of Orbit Replacement Units. There is a trade off between designing a piece of equipment to achieve a long life without intervention for maintenance, which would be complex and costly, or keeping designs less complex and, unfortunately less reliable. The simple equation is further complicated when equipment is to be upgraded as technology advances. The principal design driver at present is the scarsity of EVA resources and a drive is being made to make ORU's suitable for robotic changeout, so called Extra Vehicular Robotics (EVR). EVR forces the design process towards commonality of robotic interfaces.

A TYPICAL SPDM DESIGN REFERENCE MISSION - SSRMS Joint Drive Module Changeout

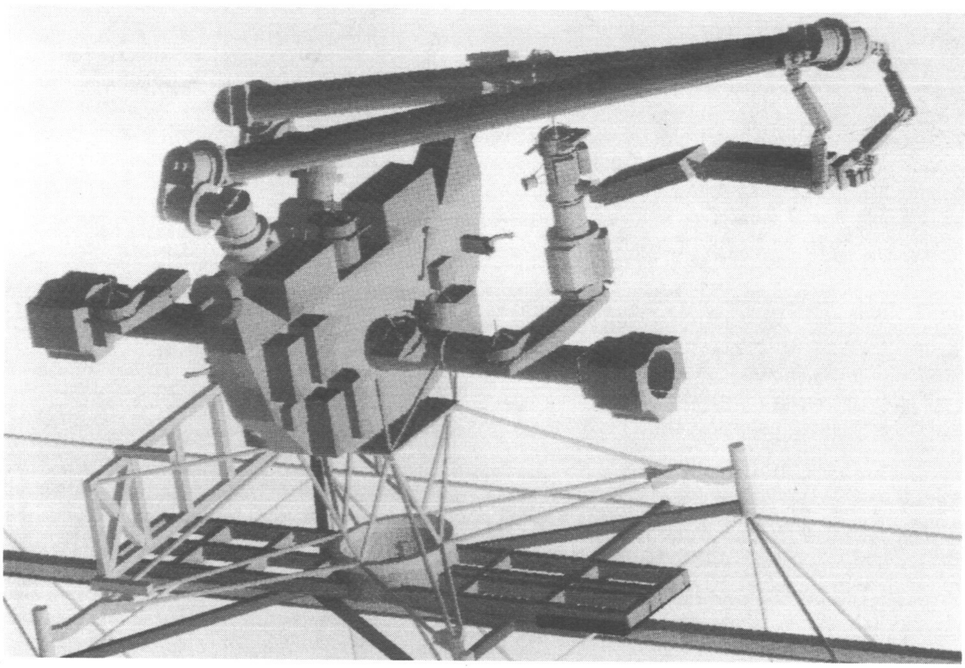
OBJECTIVE - REQUIREMENTS EXAMINED

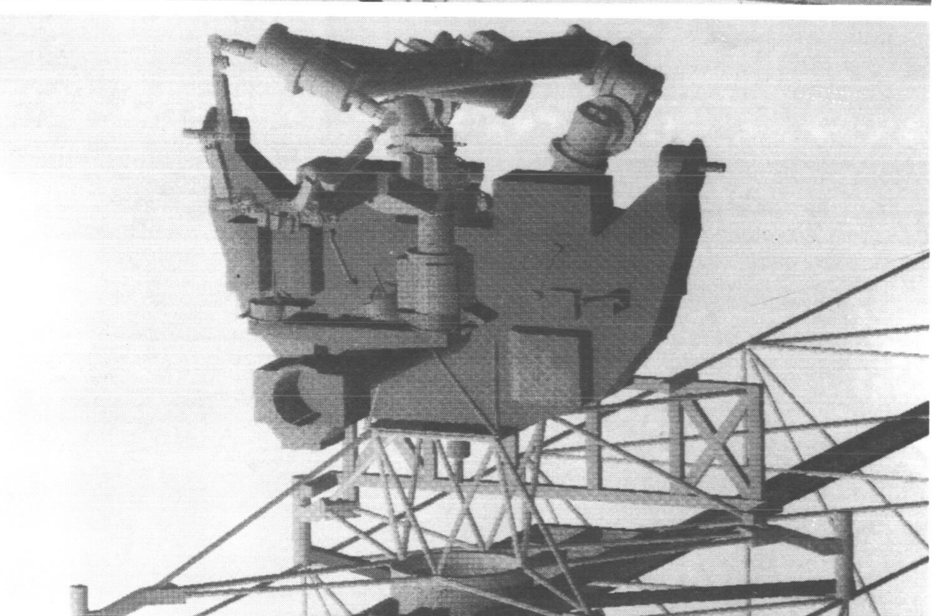
The removal and replacement of the elbow Joint Drive Module (JDM) on the SSRMS by the SPDM has been chosen as a representative example of a dextrous repair task on the MSS. The ORU changeout at the Elbow Joint demonstrates the diifculties imposed on the SPDM due to both accessibility and reach limitations. Additional requirements that are examined in this DRM are the autotrajectory and autoinsertion modes of operation as well as on board stowage of ORU's. The scenario description is given in text form together with an example of the task and sub-task breakdown.

SCENARIO DESCRIPTION

Prior to any maintenance activity the SSRMS is positioned into its maintenance configuration (*see Figures 4 & 5)* , in this position both latching End Effectors are on the MBS and the elbow joint is in the most accessible position for the SPDM. The SPDM is then unstowed from its normal PDGF.

The SPDM is placed into Auto-trajectory mode to manoeuvre close to the elbow joint and then using visual tracking and alignment the SSRMS JDM is grappled at its central interface location with one arm





FIGURES 4&5 JDM CHANGEOUT USING SPDM ON MSC VIEW 1&2

(reference arm), this arm stabilizes the SPDM throughout the removal and replacement procedure. Arm two grapples the joint Housing Locking mechanism in order to lock it prior to removal. Arm two then locks the gear train and disconnects the primary Joint Electrical Unit umbilical. The backup JEU umbilical is diconnected in the same way after which the three peripheral attachment screws are unfastened around the JDM.

Arm two releases and reattaches to a convenient latching interface location in order to counteract the forces generated by the next step in the sequence. Arm one unfastens the central tiedown screw and withdraws the defective JDM, location coordinates are stored prior to removal. The SPDM then stows the defective JDM on its ORU stowage plate and then moves to the ORU stowage location to retrieve the replacement JDM. The defective unit is swapped with the new replacement. The SPDM returns to the worksite with the new unit and using the prestored coordinates returns to a position close to the elbow.

Arm two attaches itself to its interface point using visual alignment and rereferences the coordinates. The new JDM is now inserted using a prestored Auto insertion routine. The remainder of the assembly follows the diassembly steps in reverse order.

Following completion of the JDM installation, the SPDM withdraws to a safe standby location and a functional test routine is performed to verify that full operational capability of the SRMS has been restored.

24.0 Detach Arm Two from Backup Joint Electrical Unit interface mechanism

25.0 Engage peripheral attachment screw No. 1 (7/16 Acme) interface mechanism with SPDM Arm Two

- .1 Grapple/latch locking interface with SPDM Latching/Interface tool on Arm Two
- .2 Drive latching mechanism (20 sec.)
- .3 Verify peripheral attachment screw interface latched and secured

26.0 Unfasten the peripheral attachment screw No. 1 (7/16 Acme) with SPDM Arm Two

- .1 Rotate CCW until stop is engaged

27.0 Detach SPDM Arm Two from peripheral attachment screw No. 1 (7/16 Acme)

28.0 Engage peripheral attachment screw No. 2 (7/16 Acme) interface mechanism with SPDM Arm Two

- .1 Grapple/latch locking interface with SPDM Latching/Interface tool on Arm Two
- .2 Drive latching mechanism (20 sec.)
- .3 Verify peripheral attachment screw interface latched and secured

29.0 Unfasten the peripheral attachment screw No. 2 (7/16 Acme) with SPDM Arm Two

- .1 Rotate CCW until stop is engaged

30.0 Detach SPDM Arm Two from peripheral attachment screw No. 2 (7/16 Acme)

31.0 Engage peripheral attachment screw No. 3 (7/16 Acme) interface mechanism with SPDM Arm Two

- .1 Grapple/latch locking interface with SPDM Latching/Interface tool on Arm Two
- .2 Drive latching mechanism (20 sec.)
- .3 Verify peripheral attachment screw interface latched and secured

32.0 Unfasten the peripheral attachment screw No. 3 (7/16 Acme) with SPDM Arm Two

EXAMPLE OF TASK/SUBTASK BREAKDOWN

DRM ANALYSIS AND DERIVED REQUIREMENTS

From the detailed analysis and simulations there were a number of requirements that needed refinement and a number of issues.

1) The body length needed to be extended to reach the elbow.
2) Tools and Tooling requirements needed refinement for specific JDM changeout tasks.
3) IVA control and timelines were not investigated and require further study, particularly when using two arms in a coordinated fashion.
4) Viewing and lighting need further investigation.

OTHER DESIGN REFERENCE MISSIONS INVESTIGATED

In order to encompass all the SPDM requirements of routine maintenance, Assembly, Payload servicing, Space Station servicing and ORU changeout a number of other DRM's have been investigated.

DRM # 2 Japanese Exposed Facility Assembly

Outboard of the Pressurized Japanese Module is an unpressurized Exposed Facility which can be assembled using a combination of the SSRMS and SPDM. This scenario examined in detail the ability of the SPDM to perform dextrous tasks on the mating interface between the EF#1 and the JEM while supporting the Exposed Facility.

DRM # 3 Structural Interface Adapter Assembly

The Structural Interface Adapter is a platform structure that is roboticaly deployed and the interfaced to the truss structure. The platform carries payloads and equipment. The SPDM was used in this DRM to illustrate Space Station Assembly tasks.

DRM # 4 Beta Gimbal Drive Motor Module Changeout.

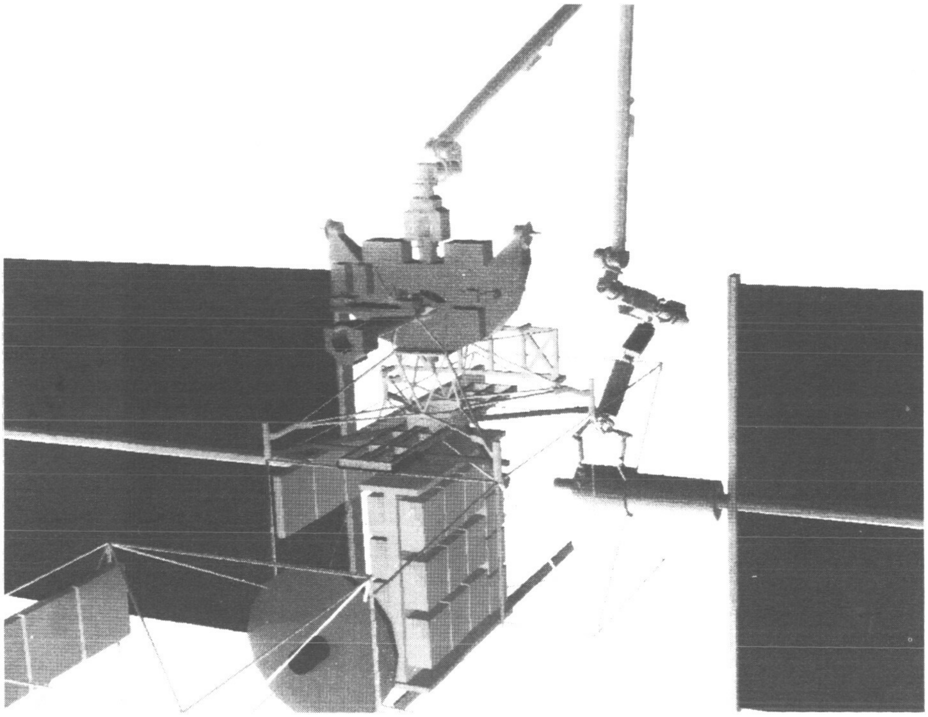


FIGURE 6 BETA GIMBAL MOTOR MODULE CHANGEOUT

Following a failure of part of the Solar Array equipment the SPDM was used to replace a motor module and restore the facility to full function. Dextrous operations in confined areas was the particular challenge in this DRM.

CONCLUSIONS

This paper has detailed the Operations Analysis conducted with Design Reference Mission development and the requirements that have been derived for the SPDM. In particular a DRM has been detailed which illustrates the ability of the MSS to perform self maintenance. By evaluating representative Missions, Tasks and Sub-tasks it is possible to carefully and systematically derive practical and achievable requirements and refine basic operational concepts.

FUTURE OPERATIONS

SPAR will continue operational analysis of Design Reference Missions to further refine the requirements for the SPDM. The IRIS 4D/70 GT will continue to be a valuable resource for kinematic simulations, the DENEB software is currently being enhanced so that dynamic algorithms can be implemented so that arm trajectories can be planned and evaluated.

A full scale 1G test rig called the SPDM Ground Testbed is presently being used for task assessment, tool development and ORU interface evaluation.

An Operations Simulation Facility (OSF) is presently being constructed at SPAR which will be a full scale representation of a Space Station Cupola control station with hand controllers and realistic controls. The views from the Cupola windows and workstation monitors will be simulated to represent views of the unpressurized environment. The degree of fidelity expected will allow greatly enhanced DRM operations analysis. The OSF will be of particular use in the evaluation of the Human Computer Interface and for the evaluation of Human in the Loop responses.

A Manipulator Development Simulation Facility will ultimately provide real time operator in the loop dynamic simulations of the MSS. High Fidelity mock ups of the Cupola, node, and orbiter aft flight deck will be integrated with MDSF. Ultimately, Station astronauts will be able to operate the MSS system from the Cupola workstation and examine the telerobotic responses of the SPDM in real time, and be trained in its operation.

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